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Measurement of Total Acoustic Power of Sources of Sound in a Reverberation Chamber.

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Measurement of Total Acoustic Power of Sources of Sound in a Reverberation Chamber.

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Report from the Laboratory of Technical Physics,

The Technical University of Denmark,

by K.A. Mørch.

ACTA POLYTECHNICA SCANDINAVICA

Physics including Nucleonics Series No. 8

(AP 286, 1960)

S U M M A R Y

The report summarizes the theory of the reverberant sound field, and an account of the reverberation chamber investigations at the laboratory is given. The reverberation chamber is to be used for measurement of the total acoustic power of sources of sound. Investigations have been carried out at frequencies between 2 and 15 kc/s.

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Measurement of the total acoustic power of sources of sound.

The total acoustic power of a source of sound can be measured in a free field or in a reverberation chamber. Using the former method, the source of sound is placed in a totally sound-absorbing room, and the sound intensity is determined all over a sphere around the source. Then the total emission is obtained by integration (summation) over the sphere of intensity multiplied by area.

It is, however, difficult to make a totally sound-absorbing room, and a considerable number of intensity measurements on the above-mentioned sphere are required to obtain a satisfactory determination of the acoustic power.

The second method of measuring - the reverberation chamber method - cannot be expected to give quite as accurate results, but on the other hand a few measurements of the sound pressure level in the chamber, are sufficient.

The reverberation chamber is a chamber constructed of highly sound reflecting materials. The method of measurement is based on the assumption of a uniform distribution of sound energy throughout the chamber, and it is also desireable that the flow of sound energy everywhere is uniformly distributed in all directions. This is a diffuse sound field, and it can only be approximated.

W.C. Sabine has shown[1)] that the total acoustic emission from a source of sound W in a reverberation chamber is

$$W = \frac{\overline{p^2}}{\rho c} V \left(\frac{\bar{\alpha}}{l} + m \right) \qquad (1)$$

where

$\overline{p^2}$ - mean square value of the sound pressure in the chamber

ρ - density of the medium in the chamber

c - velocity of sound in the chamber

V - volume of the chamber

$\bar{\alpha}$ - mean energy absorption coefficient of the reflecting surfaces of the chamber

l - length of mean free path between reflections

m - attenuation coefficient of the medium in the chamber

The formula is valid only if $\bar{\alpha} \ll 1$ and $ml \ll 1$. For frequencies up to at least 30 kc/s $\bar{\alpha}$ can be kept sufficiently low by using suitable materials for the chamber, whereas ml for increasing frequencies can be limited only by reduction of l. This means reduction of the size of the chamber, and as small chambers cannot be used for low-frequency measurements (see the theory of reverberant sound fields) it is seen that a reverberation chamber can be used only in a certain frequency interval.

<u>The theory of the reverberant sound field.</u>

The theory of the reverberant sound field has been treated out by <u>R.V. Waterhouse</u> [2]. According to this theory the energy density of the sound field will depend on the distance from reflecting surfaces, but at distances beyond one wavelength the energy distribution will be nearly uniform.

To compute the sound field near to a plane absolutely reflecting surface the assumption is made that it consist of plane sine waves, and that the flow of sound energy is uniformly distributed in all directions.

At a point (x,0,0), fig. 1, an incident wave front of plane sine waves with pressure amplitude 1 and angular frequency ω will cause a pressure variation $p = \cos \omega t$. The reflecting sur-

face is the YZ-plane through $x = 0$, and the angle of incidence is θ, the reflected wave causes an increase of pressure $\cos(\omega t + 2kx \cdot \cos\theta)$, where the wave number $k = 2\pi/\lambda$.

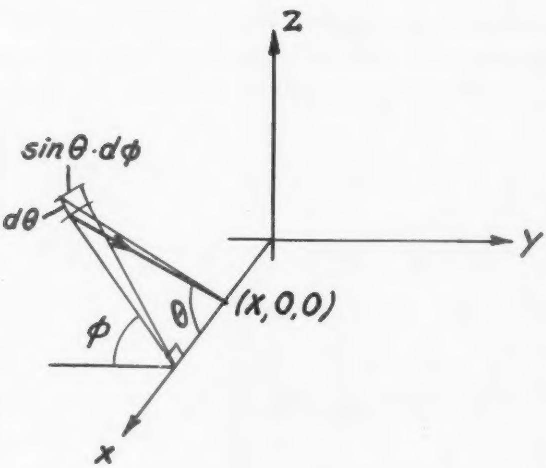


Fig. 1.

The resulting pressure variation is thus

$$p = \cos\omega t + \cos(\omega t + 2kx \cdot \cos\theta),$$

and the mean square value of the sound pressure

$$\overline{p^2} = 1 + \cos(2kx \cdot \cos\theta). \qquad \text{fig. 2}$$

The assumption of even distribution of energy flow in all directions gives the resulting sound pressure at $(x,0,0)$

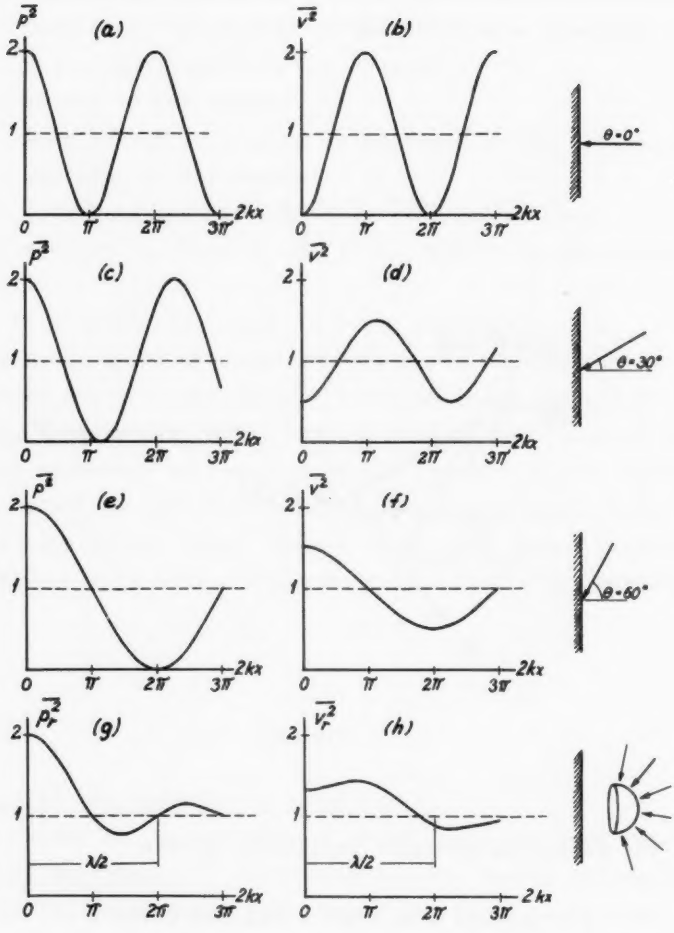


Fig. 2.

Mean square value of sound pressure and particle velocity at a plane totally reflecting wall. (a) - (f) shows the distribution in a sound field composed of plane waves with angle of incidence 0°, 30° and 60°, whereas (g) - (h) shows the distribution in a reverberant sound field.

$$\overline{p_r^2} = \frac{1}{2\pi}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi/2} \overline{p^2}\ \sin\theta\cdot d\phi\cdot d\theta \qquad \text{(see fig. 1)}$$

$$\overline{p_r^2} = 1 + \frac{\sin 2kx}{2kx} \qquad \text{fig. 2}$$

The particle velocity at the point (x,0,0) can be found in a similar way. The only difference is that the particle velocities are vectors (fig. 3), whereas the pressures are scalar quantities.

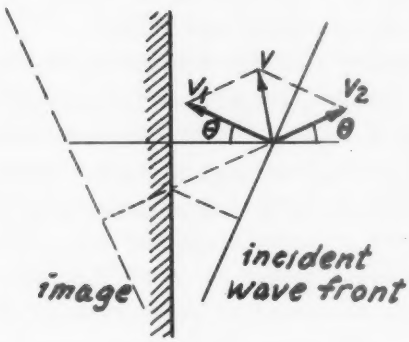


Fig. 3.

Particle velocity at a reflecting wall. It is obtained through vector addition of the particle velocities of the incoming and the reflected sound wave.

For waves with angle of incidence θ the mean square volocity is

$$\overline{v^2} = 1 - \cos(2kx\cdot\cos\theta)\cdot\cos2\theta, \qquad \text{(fig. 2)}$$

and with uniform flow of energy in all directions the resulting particle velocity becomes

$$\overline{v_r^2} = 1 - \frac{\sin 2kx}{2kx} + \frac{\frac{\sin 2kx}{2kx} - \cos 2kx}{k^2x^2}$$

see fig. 2

The energy of the sound field at $(x,0,0)$ is both potential and kinetic, and thus the energy distribution at a plane reflecting wall is given by

$$\overline{E} = 1 + \frac{\frac{\sin 2kx}{2kx} - \cos 2kx}{2k^2x^2}$$

From this it is seen that the reverberant sound field, even though the motion of energy is uniform in all directions, is far from being diffuse near reflecting surfaces, as the energy level is dependant of the distance from these.

At some distance from the reflecting surfaces the energy distribution is nearly uniform, and the sound field is suitable for intensity measurements. However, as the energy density near the surfaces is greater than at some distance, the intensity measured is not the mean intensity of the chamber, and it has therefore to be corrected.

The correction factor is

$$R = 1 + \frac{S}{V}\int_0^\infty \frac{\sin 2kx}{2kx}\,dx = 1 + \frac{S}{V}\cdot\frac{\lambda}{8}$$

where S is the reflecting area. It is assumed that the dimensions of the chamber are large compared with the wavelength.

For the chamber at this laboratory (LTP) $S = 6{,}5\ m^2$ and $V = 0{,}8\ m^3$, and hence $R = 1 + \lambda$ (λ in metres).

Near edges and corners the increase in energy density is greater than at plane surfaces, but on the other hand, these regions are small compared with the surface regions, and they can therefore be ignored.

In practice it is not possible to fulfil the assumptions of the theory of the reverberant sound field, as neither plane waves nor uniform energy flow in all directions are possible. However, the approximation has proved to be sufficient to confirm the theory by experiments carried out first by R.V. Waterhouse at the National Bureau of Standards (NBS), and later here at LTP.

Investigations at LTP.

In connection with the technical problems dealt with at the laboratory it has often been necessary to know the total acoustic power of different sources of sound, and until now this has been found by free field measurements [3]. To avoid the considerable work connected with the use of this method, Professor R.E.H. Rasmussen, LTP, desired an investigation of the possibilities of using the reverberation chamber method.

The investigations at NBS were carried out in a reverberation chamber whose dimensions were 8,2 x 9,8 x 6,6 m. In the frequency range up to 5 kc/s it was found that the intensity distribution around the source of sound used could be considered to be uninfluenced by the radiation pattern, and the measurements were satisfactory up to 7 kc/s. At higher frequencies the radiation pattern broke through owing to increased air absorption, and the accuracy of the measurements was reduced.

At LTP interest has been mainly centred on measurements at rather high frequencies, and the investigations dealt with in this paper are carried out at frequencies of between 2 and 15 kc/s.

The LTP reverberation chamber has a volume of 0,8 m^3. It is constructed of a cubic sheet iron box (thickness of plate 5 mm), the opposite sides of which are made non-parallel by lining with concrete on the three sides (fig. 4). It is fitted with a large fan having four two-piece, very irregular vanes. The purpose of the fan is to ensure uniform energy distribution and flow in all directions.

Condenser microphones - a 1 inch and a 1/2 inch microphone - were used for the sound pressure measurements. The 1/2 inch micro-

phone, which was kindly lent to us by Messrs. Brüel & Kjær, Ltd, before production was started, could be used for frequencies up to 40 kc/s, whereas the 1 inch microphone cut off at 20 kc/s. The former was less influenced by deviations from uniform distribution of energy flow, and it was therefore more suitable than the latter, at least at high frequencies.

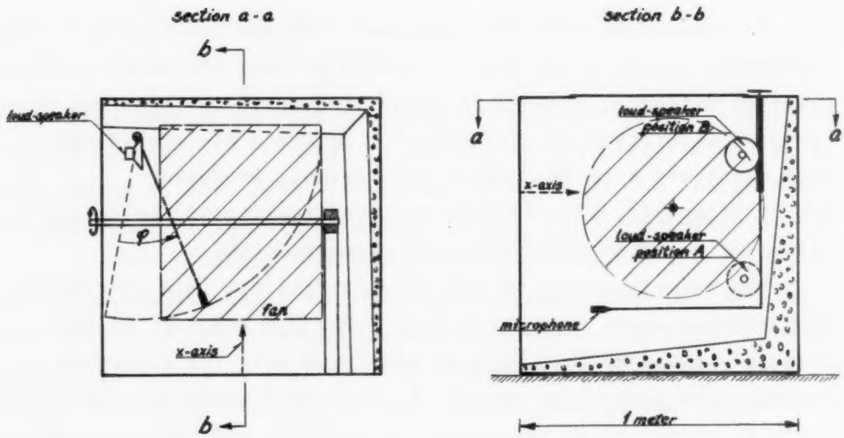


Fig. 4.

LTP reverberation chamber.

The source of sound was a loud-speaker. Especially at high frequencies the radiation is directional. The loud-speaker is thus a suitable source of information on the qualities of the chamber. In fig. 5 a and b the radiation pattern is shown at 7 and 15 kc/s.

As seen from fig. 4, the fan fills up all the central part of the chamber, so that this region cannot be used for measuring. The present measurements are carried out partly along the "x-axis" shown, and partly along a 100 degree circular arc placed below the fan. The axis is to some extent protectet from direct irradiation from the source of sound.

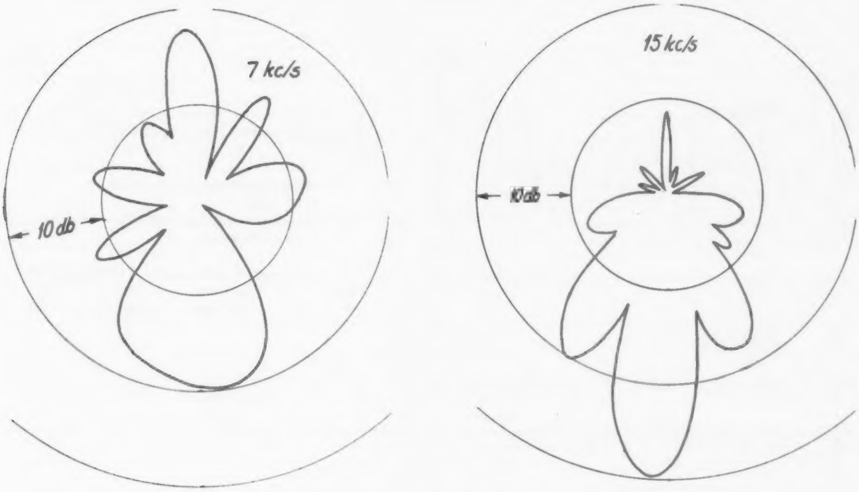


Fig. 5 a. Fig. 5 b.

Loud-speaker radiation pattern at 7 and 15 kc/s.

To study the intensity pattern around the loud-speaker, it was placed as near as possible to the centre of the arc, just above the plane of the circle (orientation: $\varphi = 92°$, fig. 4), and the intensity along the arc was measured. The measurements, being marked "circle,A", are shown in fig. 6. The radiation pattern of the loud-speaker does not show under 15 kc/s, and at this frequency it is only slightly visible. At all frequencies the intensity is well smoothed out.

Measurements along the same circle, but with the loud-speaker mounted at the top of the chamber (approximately symmetrically with respect to the horizontal central plane of the chamber), has given the results depicted in fig. 7 a, being marked "circle,B". During these measurements, the microphone was fairly well protected from direct irradiation, and the intensity distribution along the circle was at all frequencies very uniform. A single series of measurements at 15 kc/s showed increasing intensity in the re-

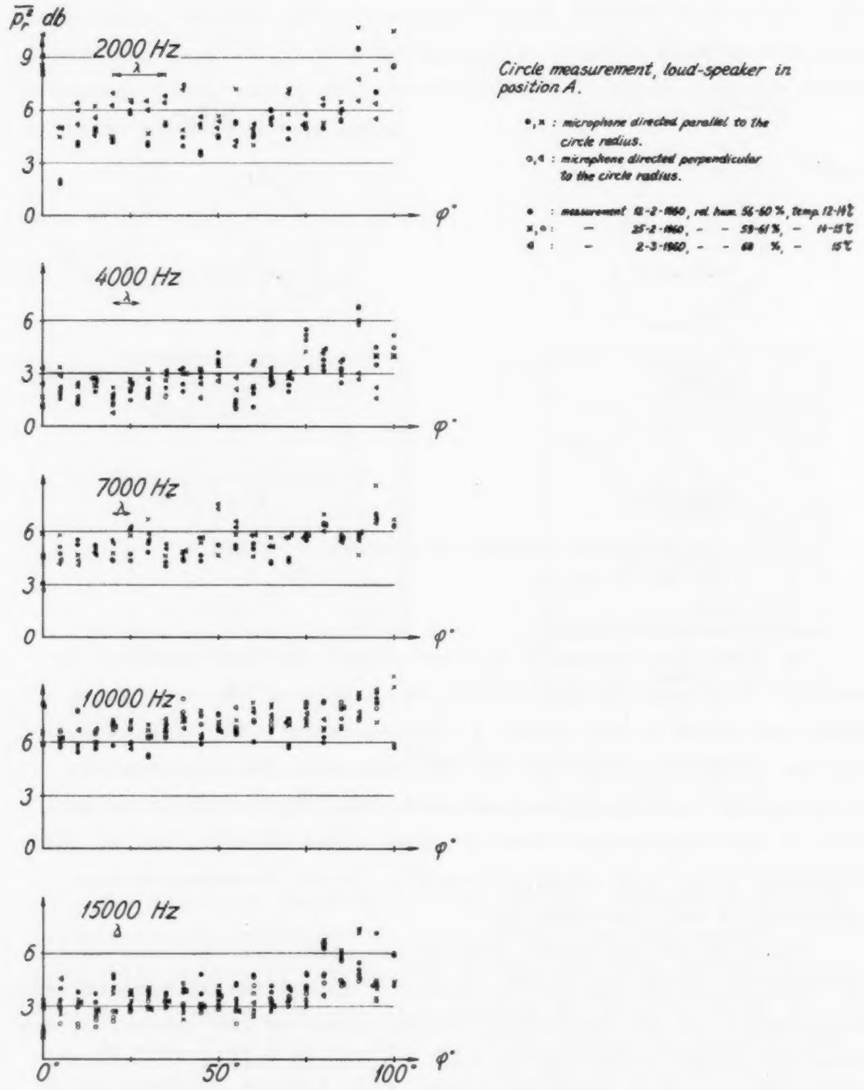


Fig. 6.

Circle,A measurements.

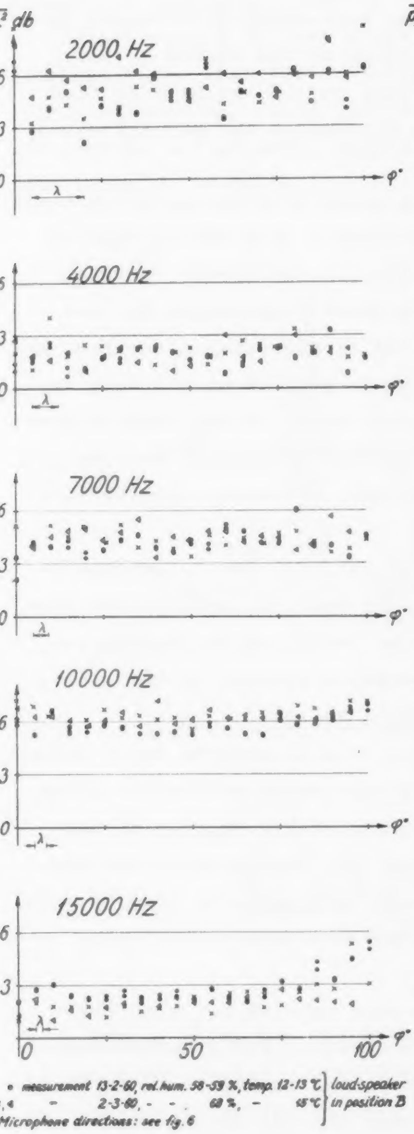


Fig. 7 a.

Circle,B measurements.

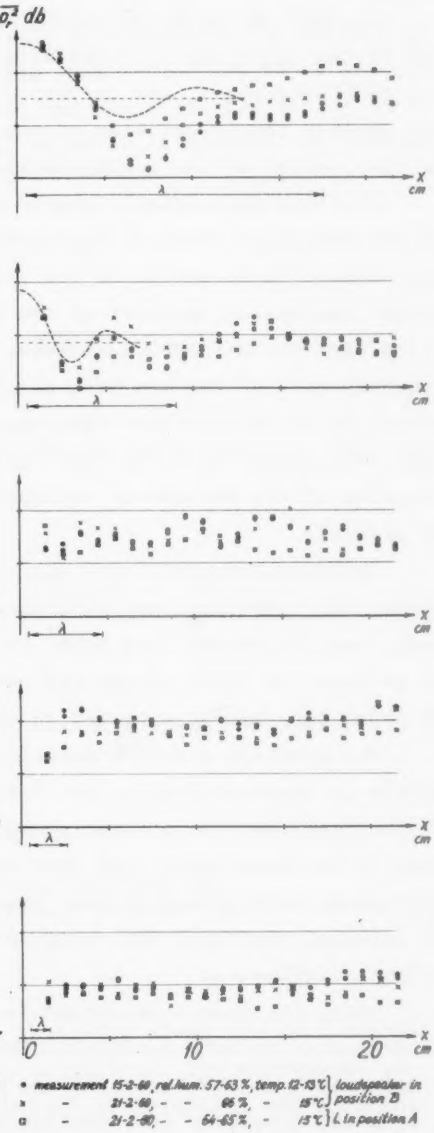


Fig. 7 b.

Axis,A and axis,B measurements.

gion in front of the loud-speaker, but this has proved not to be reliable.

For all circle measurements the microphone was mounted in one of two positions - in the direction of the radius of the circle (outwards), and perpendicular to the radius - to find out whether the orientation of the microphone had any influence on the results of the measurements.

Circle,A measurements showed a pronounced intensity increase in the region in front of the loud-speaker when the microphone was mounted in direction of the radius of the circle. Only a slight increasing tendency at the highest frequencies was measured when the microphone was mounted in the other direction. Along the rest of the arc both positions gave about the same results. It is thus evident that, just in front of the loud-speaker, where the radiation field has a preferred direction, and the orientation of the microphone is important, erroneous results will be probable.

These measurements were carried out with the 1 inch microphone, but investigations with the 1/2 inch microphone were also made, and the chamber was found to be useful up to frequencies of at least 15 kc/s, though the radiation pattern of the source of sound here can be expected to begin to show.

The greatest standard deviation on the measured sound intensities is found at 2 kc/s, but here consideration must be given to the fact that the intensity may vary within regions of the size of the wavelength, and that both the loud-speaker and the microphone were placed so near the reflecting walls that it must be expected that both the emission and the measurements were slightly influenced.

Along the x-axis measurements were carried out with the loud-speaker in both positions. The results, being marked respectively "axis,A" and "axis,B", are depicted in fig. 7 b. At 2 and 4 kc/s the intensity distribution near the reflecting wall (x=0), calculated from the theory of the reverberant sound field, is sketched in. The agreement between the theoretical and the actual sound field is absolutely satisfactory. At higher fre-

quencies the wavelength is so small that the microphone cannot record the intensity pattern.

Measurements of mean intensity should not be carried out at distances less than one wavelength from reflecting walls because of the reverberant sound pattern, and therefore the x-axis does not provide a reasonable length, on which to measure, at frequencies below 3 - 4 kc/s.

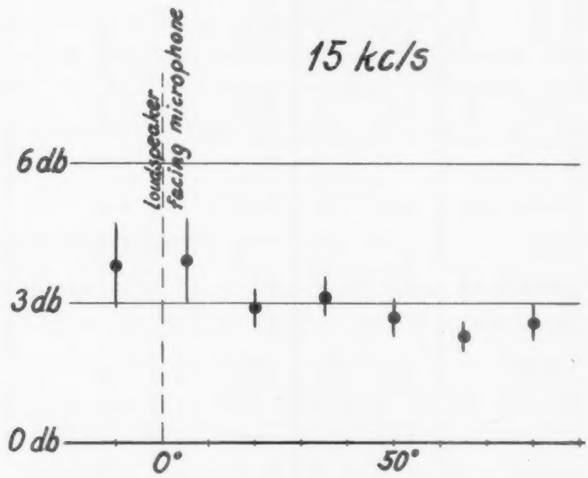


Fig. 8.

Mean sound intensity along the x-axis at different orientations of the loud-speaker (B-position).

Fig. 8 shows how the mean intensity along the axis depends of the loud-speaker orientation at 15 kc/s. The microphone is not completely protected from direct irradiation, and when the loud-speaker is directed towards the axis the mean intensity and the standard deviation are also found to be higher than they are for other directions. It is thus necessary to conclude that direct irradiation must always be avoided when making reverbera-

TABLE 1

m - mean value, s - standard deviation

measurement		2 kc/s		4 kc/s		7 kc/s		10 kc/s		15 kc/s	
		m db	s db	m db	s db	m db	s db	m db	s db	m db	s db
Circle,A											
1	•	4.9	.7	2.2	.8	4.7	.5	6.1	.6	3.9	.5
2	×	5.5	.9	2.6	.6	5.3	.7	7.0	.7	3.1	.6
3	○							7.1	.6	2.9	.6
4	◁	5.9	.9	2.6	.7	5.5	.9	6.9	.7	3.3	.5
Circle,B											
1	•	4.8	1.1	1.8	.6	4.2	.6	5.8	.5	2.5	.4
2	×	4.9	.8	2.3	.6	4.4	.5	6.4	.5	2.0	.6
3	◁	5.8	.8	1.9	.6	4.5	.6	6.2	.4	2.0	.4
Axis,A											
2	□	(6.2)		2.2	.4	3.9	.4	5.2	.4	2.2	.3
Axis,B											
1	•	(4.3)		2.6	.7	4.7	.6	6.0	.5	3.0	.4
2	×	(4.5)		2.7	.5	4.5	.5	5.6	.5	2.7	.4
Mean value of series of measurements stated		5.2	.7	2.3	.4	4.6	.5	6.2	.6	2.8	.6

Table 1 shows mean values and standard deviations for the reverberation chamber measurements depicted in figs. 6, 7a and 7b. Regions up to one wavelength from reflecting walls are omitted from the calculations, and for circle,A measurements the region $\varphi = 75° - 100°$ is excluded. A few undoubtedly false measurements in the region directly in front of the loud-speaker are omitted from circle,B calculations.

tion chamber measurements.

In table 1 mean values of the measurements depicted in fig. 6, 7 a and 7 b are given, and standard deviations are computed both for the individual series of measurements and for the mean values found.

The standard deviation for the individual series of measurements is a measure of the deviation from a uniform energy distribution, and it is seen that, especially at high frequencies, good smoothing is obtained.

The standard deviation for the mean values of the measurements can be taken to be a measure of the errors involved in the determination of the mean sound intensity. Thus the mean intensity in the chamber in the frequency interval from 2 to 15 kc/s can be expected to be measured <u>with an error not exceeding 0.6 - 0.7 db.</u>

<u>Measuring of acoustic power.</u>

The acoustic power of a source of sound is determined from equation (1) $W = \overline{p^2} V \, (\bar{\alpha}/l + m)/\varrho c$. Here V, ϱ and c can be found easily, with small errors, and if the source of sound emits pure sine waves m can be taken from tables. Only $\bar{\alpha}/l$ remains to be found. This figure can be expected to be approximately constant within the frequency interval dealt with in this paper, possibly increasing slowly with increasing frequency. Values of $\bar{\alpha}/l$ are found by measuring the total acoustic power of a loud-speaker both in a free field and in the reverberation chamber. The results are shown in fig. 9. Because of insufficient free field measurements the error is 30 - 40%, and accordingly the error on acoustic power calculations becomes about 1,5 db. However, accurate free field measurements can bring this down to about 0,7 db.

If the source of sound does not send out pure sine waves it is not easy to determine m - the Hartmann generator, for example, radiates sound, the fundamental (and dominating) tone of which is attenuated much more strongly than would be expected. It is therefore better to determine $(\bar{\alpha}/l + m)$ in another way. <u>R.W. Young</u> has proposed measuring the decay rate of the sound pressure level in

the reverberation chamber [4].

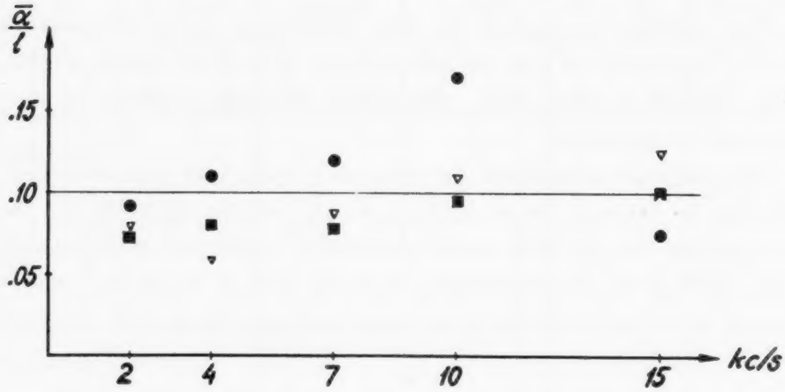


Fig. 9.

Determination of $\bar{\alpha}/l$ for the LTP reverberation chamber.
- ● free field - reverberation chamber measurement method
- ■ sound pressure decay method, fan rotating
- ▽ sound pressure decay method, fan stopped

An expression for the decay rate can be found as follows. The symbols used are

L_t - sound pressure level in db at the time t

D - decay rate of the sound pressure level in db/sec

t - time in sec

$\bar{r}$ - mean energy reflection coefficient for the reflecting surfaces, $\bar{r} = 1 - \bar{\alpha}$

$$L_t = L_{t=0} - D \cdot t$$

and

$$D = -\ 10\ \frac{c}{l}\ \log\ \bar{r} - 10\ \log\ e^{-mc}$$

which can be written

$$D = 10\ \log\ e \cdot c\ (\bar{\alpha}/l\ (1 + \bar{\alpha}/l + \cdot\ \cdot) + m)$$

As $\bar{\alpha} \ll 1$ terms of higher order can be omitted

$$D = 4{,}34\ c\ (\bar{\alpha}/l + m) \qquad (3)$$

and (1) becomes

$$W = 0{,}23\ \frac{\overline{p^2}}{\varrho c^2}\ V \cdot D \qquad (1a)$$

In small reverberation chambers it is not easy to measure the dacay rate as it is rather high. For the LTP reverberation chamber it is thus found that the smallest possible decay rate is about 120 db/sec ($m = 0$, $\bar{\alpha}/l = 0{,}8$).

However, it has proved to be possible to measure the decay rate with an oscillograph. In connection with these investigations oscillograms of the sound picture were taken during normal use of the chamber.

The oscillograms show that the momentary sound pressure at a certain point depends on the position of the fan. In fig. 10 oscillograms are shown for 2 and 15 kc/s with the fan rotating at 120 r.p.m. The sound pressure oscillates rather irregularly, but characteristic shapes of the sound picture reveal that it is not random, but that it has a period equal to the time of revolution of the fan. This is especially easy to see at low frequencies.

The decay process is photographed both with the fan rotating (120 r.p.m.) and stopped. When the fan is stopped it is possible to find positions of the fan which result in very regular decay curves, but then the decay rates are found to be so great that they are without doubt false. For arbitrary fan positions

most of the decay curves are useful, and the decay rates are in agreement with other measurements, but it is necessary to take several decay curves to obtain small errors.

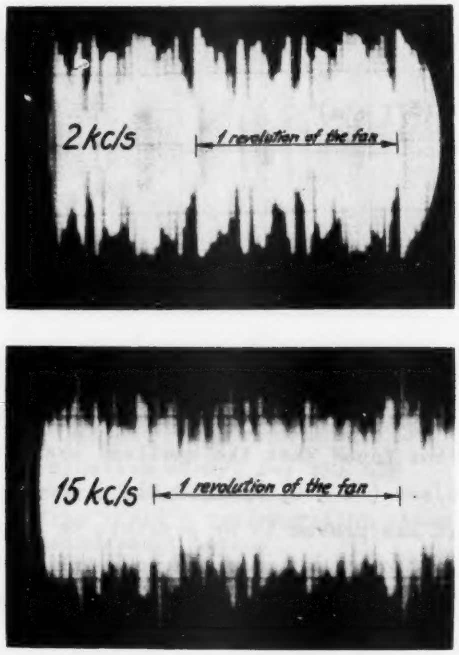


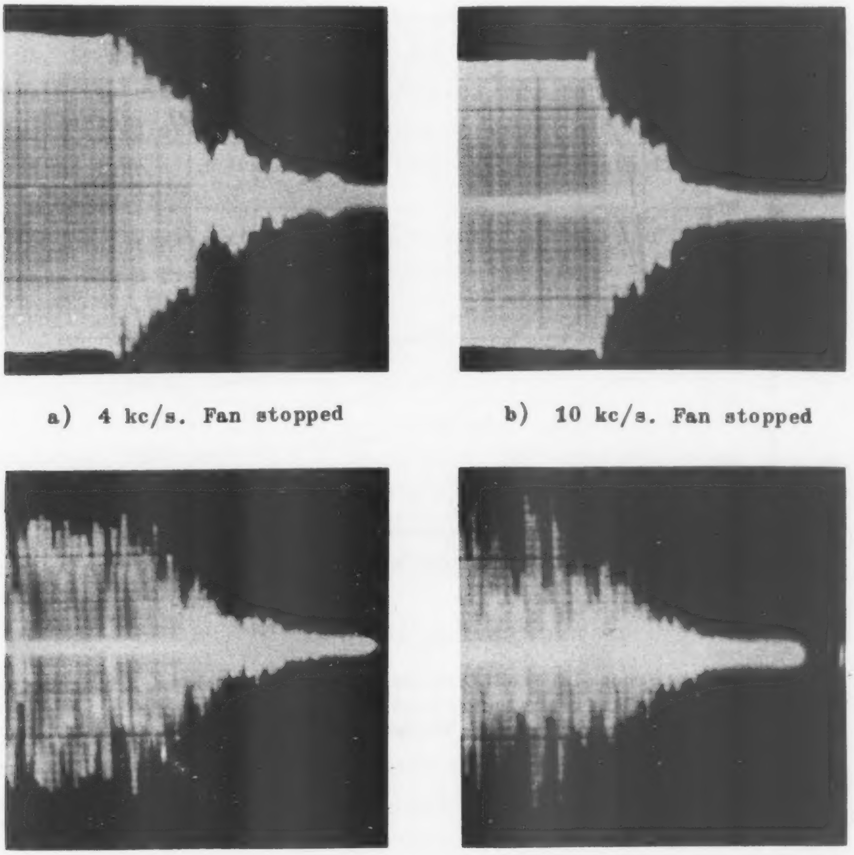
Fig. 10.

Oscillograms of the sound pressure in the reverberation chamber.

The best decay rate measurements were made with the fan rotating. All pictures were useful, and the standard deviation for the measurements was never greater than 20%. This method is thus found not only to be convenient, but also quite accurate, and undoubtedly it will be possible to develop the method so that even better accuracy can be obtained.

Decay rate measurements in a free field have proved that the

loud-speaker was effectively stopped instantaneously, and that the microphone was able to record an equally rapid decay of the sound level.



a) 4 kc/s. Fan stopped

b) 10 kc/s. Fan stopped

c) 4 kc/s. Fan rotating

d) 10 kc/s. Fan rotating

Fig. 11.
Decay curves.

In fig. 9 are shown values of $\bar{\alpha}/l$ found by measurement of decay rates, and in fig. 11 examples are given of pictures of decay processes.

In the frequency interval dealt with it is found that $\bar{\alpha}/l \approx 0,8 - 1,2$. l is about $4 \cdot V/S$. Thus $l \approx 0,5$ m and $\bar{\alpha} \approx 0,4 - 0,6$. The value of l is not very accurate, but a value $\bar{\alpha} \approx 0,4$ was expected.

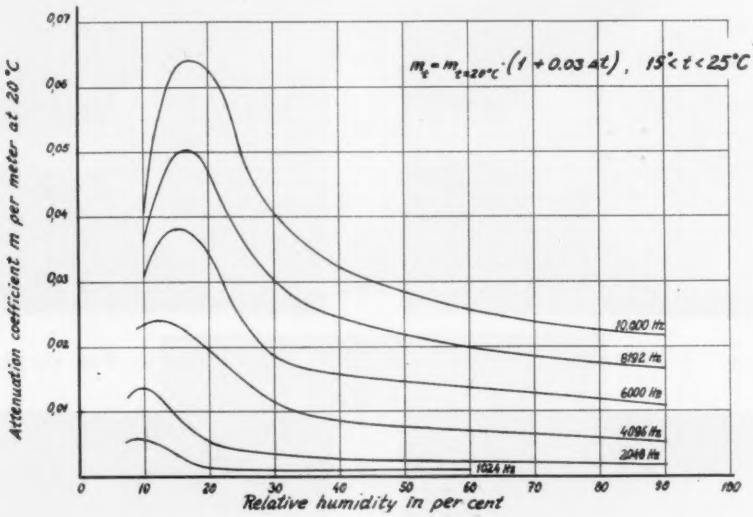


Fig. 12.

Attenuation coefficient m. (After Knudsen and Harris: Acoustical Design in Architecture, (J. Wiley 1950)).

The investigations carried out in the NBS reverberation chamber showed that the chamber could be used for measurements up to 7 kc/s. At this frequency ml is about 0,09. For the LTP reverberation chamber ml is at 15 kc/s about 0,03, and thus the chamber is expected to be of use also at somewhat higher frequencies than 15 kc/s. In these estimates a relative humidity of 50 - 60% has been assumed, but the air attenuation coefficient is greatly dependent on the humidity, fig. 12.

Summary.

The investigations at the Laboratory of Technical Physics have shown that it is possible to measure the total acoustic power of a source of sound at frequencies of between 2 and 15 kc/s in a reverberation chamber of volume 0,8 m^3 with an error of 1 db. It is sufficient to carry out measurements at a few points within the chamber, but the microphone must be protected from direct irradiation from the source of sound, and the measurements must be made at distances more than one wavelength from reflecting walls.

The investigations have confirmed the theory of the reverberant sound field.

Acknowledgement.

For valuable discussions and helpful suggestions I thank Professor, Dr. Phil. R.E.H. Rasmussen, Assistant Professor L. Løgstrup Jensen and Engineer S.J. Gjendal.

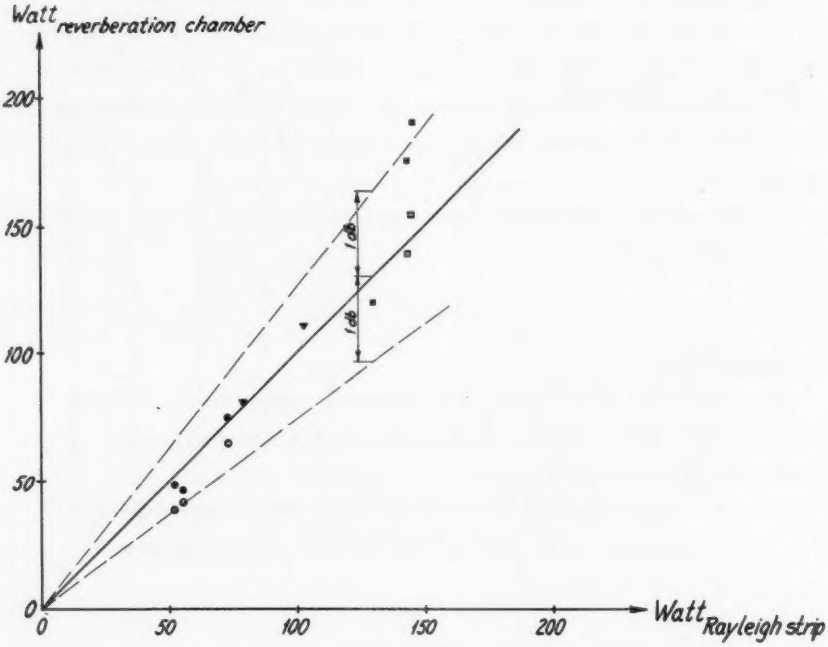
The investigations dealt with in this paper were carried out in collaboration with the Danish Defence Research Board.

Appendix.

Some measurements of the total acoustic power of Hartmann-generators were carried out in the reverberation chamber. Two different generators were used, and the results were compared with those obtained by Jul. Hartmann (1936-37) during free field measurements with Rayleigh-strips, fig. 13.

The generator used by Hartmann was especially designed for free field measurements, and it was not identical with any of those used for the reverberation chamber measurements. The calculations of the acoustic power made by Hartmann were based on the Rayleigh-disk theory by König [5]. However, an improved theory is made by H. Højgaard Jensen and K. Saermark [6] and accor-

ding to this the calculations made by Hartmann can be expected to be about 3, 4 and 5 % too great at 9, 11 and 13 kc/s respectively.



Measurement of total acoustic power of Hartmann-generators.

Analogous measurements carried out in a free field with Rayleigh-strips (Jul. Hartmann) and in the reverberation chamber.

- • generator 2, ○ – 1 } $d_0 = d = l = 4$ mm, 13 kc/s
- ▾ generator 2 $d_0 = d = l = 5$ mm, 10-11 kc/s
- ▪ generator 2, ▫ – 1 } $d_0 = d = l = 6$ mm, 9 kc/s

Fig. 13.

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